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Investigating the Energy Consumption of an IEEE 802.11 Network Interface

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Abstract

This report describes a series of simple experiments which measure the per-packet energy consumption of an IEEE 802.11 wireless network interface. The goal of this work is to develop a solid experimental basis for assumptions that can (or cannot) be made in the design and analysis of network protocols operating in the ad hoc wireless environment.

Keywords: wireless network interface, IEEE 802.11, energy consumption, energy-aware network protocols, ad hoc networks, measurement

1 Motivation

Energy consumption at the network interface is an issue for all mobile computing devices, whether they operate within a base-station infrastructure or in a free-standing mobile ad hoc network (manet).

In a wireless ad hoc network, a host communicates directly with hosts within wireless range and indirectly with all other hosts using a dynamically-computed, multi-hop route via the other hosts of the manet. There has been a great deal of interest in the design and analysis of network protocols for this environment.

It has recently been suggested that it is important to understand the energy consumption behaviors of *network-layer* protocols in ad hoc networks[1]. Such work has been limited by lack of information about the energy consumption of wireless network devices.

Key questions include:

- *What implications does ad hoc (versus base station) mode operation have on energy consumption?*

  A base station is usually responsible for scheduling communication with the mobiles and buffering traffic for sleeping hosts. The base station usually has no energy constraints, so any such activity that the mobile can offload onto the base station is effectively "free". In an ad hoc network, there are no base stations to provide this service.

- *Is it important to consider energy consumption and bandwidth independently?*

  Most wireless network performance analyses consider only bandwidth. If energy consumption in an ad hoc network is generally proportional to bandwidth – if it can be reasonably well described in terms of the number of packets or bytes sent – there is no network layer specific strategy for reducing energy consumption. In this case, traffic balancing becomes the key energy management concern. Battery power is a non-renewable resource: when a host's batteries fails, it fails. Moreover, a failed host can adversely impact the connectivity of the ad hoc network.

  However, the signal transmitted by a wireless host affects every live receiver within range of the sender. Whether the signal is received as point-to-point or broadcast traffic or is discarded, energy is consumed at every receiver. The number of receivers will be determined by the transmission range and the local node density. In general, there will be several receivers, magnifying the costs of receiving and discarding traffic. This suggests that there is some value in answering the following questions:

  – What are the relative costs of sending, receiving and discarding traffic?

– What are the relative costs of point-to-point and broadcast traffic?

– What are the relative costs of channel access and data transmission?

The experiments described in this report attempt to answer these questions. The results indicate that energy consumption is not analogous to bandwidth usage: protocols that assume otherwise may show undesirable "energy-oblivious" behaviors. The value of this work is therefore to develop a solid experimental basis for energy-related assumptions to be made in the design and analysis of energy aware network protocols for ad hoc wireless networks.

2 Related Work

Despite a great deal of activity in the area of energy management for mobile computing, there seem to be very few published measurements of the energy consumption of network devices. In particular, there are no published measurements of the per-packet energy consumption of an IEEE 802.11 network interface.

In [3], Robin Kravets and P. Krishnan have examined the power consumption of IEEE 802.11 WaveLAN PC cards, emphasizing operation in conjunction with a base station. Their methodology is based on sampling the current draw of an otherwise idle laptop as it sends and receives traffic over an extended period of time. By comparing the total energy used while sending or receiving traffic with the energy consumed by an idle laptop, the total cost of processing traffic can be computed. This approach has the advantage of measuring total system cost, but provides less packet-oriented detail. Also, the results are potentially more dependent on particular system-wide energy management techniques than on the behavior of the network interface.

Paul Gauthier, Daishi Harada and Mark Stemm reported on packet-oriented measurements of the energy consumption of wireless interfaces in [2]. Their work included measurements of the pre-IEEE 802.11 WaveLAN 1 interface, as well as a number of other devices. The experiments described below are based on their methodology.

However, in addition to updating these results to include more recent hardware, the current work emphasizes issues associated with both ad hoc operation of the network interface and complexities introduced by the IEEE 802.11 protocol. It is also unique in investigating the behavior of non-destination hosts which overhear wireless traffic.

3 Overview

Section 4 briefly describes the IEEE 802.11 protocol for interfaces operating in ad hoc mode and presents a linear formulation for the energy consumption associated with processing a packet. Section 5 describes the experimental methodology that was used to verify the linear model and experimentally determine coefficients for use with this linear formulation. Section 6 presents oscilloscope traces showing the current draw of the network interface during various operations, giving insight into some details of the WaveLAN implementation of the IEEE 802.11 protocol. Section 7 describes how these traces were used to compute per-packet energy consumption and determine appropriate coefficients for use with the equations developed in Section 4. Section 8 presents the complete results, along with some further discussion. Section 9 suggests areas for further investigation.

4 Linear Energy Consumption Model

As a consequence of operation in ad hoc mode, a host must always be ready to receive traffic. A network interface operating in ad hoc mode therefore has constant 'idle' mode power consumption. This is different from and may be quite large compared to power consumption in the 'doze' mode, from which the interface must wake up in order to send or receive traffic.

In the absence of retransmissions, connectivity changes that occur while a packet is in flight and other anomalies, the additional energy consumed by the network interface when a host sends, receives or discards a packet can be described using a linear equation. That is, there is a fixed part associated with channel acquisition and an incremental part which is proportional to the size of the packet. Experimental results confirm the accuracy of the linear model and are used to determine values for the linear coefficients m and b for various operations.

$$Energy = m \times size + b \tag{1}$$

In contrast with bandwidth measurements, which indicate the presence or absence of traffic in the network media, measurements of energy consumption must account for the network interface's response to any signal received on the wireless interface. Meaningful packet-oriented energy consumption measurements will therefore need to consider not only sending, but also receiving and discarding traffic.

4.1 Send/Receive

The IEEE 802.11 protocol is a CSMA/CA protocol. Before sending point-to-point traffic, the source listens briefly to the channel. If it is clear, the source sends an RTS (request-to-send) control message, identifying the destination. The destination responds with a CTS (clear-to-send) message. On receiving the CTS, the source sends the data and awaits an ACK from the destination. From Equation 1:

$$Energy_{point-to-point-send} = m_{send} \times size + b_{send} \tag{2}$$

$$Energy_{point-to-point-recv} = m_{recv} \times size + b_{recv} \tag{3}$$

For IEEE 802.11 broadcast traffic, the sender listens briefly to the channel. If it is clear, the message is sent. If not, the sender must back off and retry later. The IEEE 802.11 protocol does not define broadcast acknowledgement or retransmission. It is because of these differences in the protocol that broadcast and point-to-point traffic need to be considered separately:

$$Energy_{broadcast-send} = m_{send} \times size + b_{send'} \tag{4}$$

$$Energy_{broadcast-recv} = m_{recv} \times size + b_{recv'} \tag{5}$$

The incremental cost of sending and receiving data is expected to be the same for both broadcast and point-to-point traffic. The differences in b_{recv} and $b_{recv'}$ and b_{send} and $b_{send'}$ reflect the difference between the IEEE 802.11 protocol for broadcast and point-to-point traffic.

4.2 Discard

As another consequence of operating in ad hoc mode, a network interface overhears all traffic sent to and from nearby hosts. It is therefore important to consider not only the energy consumption of sending and receiving traffic, but also the energy consumed by an interface when it processes point-to-point traffic that it will discard after determining that it is not the intended destination.

Each non-destination host overhears some or all of the IEEE 802.11 control protocol, depending on whether it is in range of the sender, the destination or both. A non-destination host in range of the sender will also overhear the data traffic. These cases need to be considered separately because the host overhears a different part of the control protocol in each case.

In range of both sender and destination:

$$Energy = m_{disc} \times size + b_{disc} \tag{6}$$

In range of sender only:

$$Energy = m_{disc} \times size + b_{disc'} \tag{7}$$

For a non-destination host in range of the sender, the value of m_{disc} is expected be at most zero. That is, ignoring any amount of data that is already known to be directed to another host should require no more power than maintaining the network interface in the idle state. A value of zero implies that the interface takes no energy-conserving strategy based on the presence of uninteresting data on the media. The difference between b_{disc} and $b_{disc'}$ reflects the difference between the portion of the IEEE 802.11 control protocol overhead by each host.

In range of destination only:

$$Energy = m_{none} \times size + b_{disc''} \tag{8}$$

As above, the differences among the values of b_{disc} reflect which portions of the IEEE 802.11 control protocol the host overhears. For a non-destination host in range of the receiver only, the value of m_{none} is also expected to be at most zero.

4.3 Promiscuous Mode Receive

A non-destination host operating its network interface in promiscuous mode eavesdrops on all point-to-point data traffic that it overhears.

In range of both sender and destination:

$$Energy = m_{recv} \times size + b_{disc} \tag{9}$$

In range of sender only:

$$Energy = m_{recv} \times size + b_{disc'} \tag{10}$$

The hosts receives the data as if it were point-to-point or broadcast traffic, so the incremental cost is expected to the same. The host also discards the IEEE 802.11 control traffic; the cost is expected to be the same as the case in which the data traffic is also discarded.

A host that is within wireless range of the destination only cannot overhear the data that is being transmitted, even if it is operating in promiscuous mode.

In range of destination only:

$$Energy = m_{none} \times size + b_{disc''} \tag{11}$$

This case is therefore expected to be the same as to the case of discarding traffic while in range of the destination only.

5 Experiments

As in the experiments reported in [2], energy consumption was determined by measuring the current flow though a small resistor placed in series with the network interface. The input voltage to the interface was assumed constant and checked before and after each series of measurements to ensure that it had not dropped due to battery discharge. The instantaneous power consumption is the product of the current and input voltage and energy consumption is the integral of the power consumption over time.

Figure 1: Sycard PCCextend CardBus Extender

5.1 Power Characteristics

The experiments were conducted using a 2.4GHz Lucent IEEE 802.11 WaveLAN PC card[4], which is popular and widely available. Its published power characteristics are shown in Table 1. The published specifications for other popular IEEE 802.11 cards (e.g. Aironet) are similar. However, specific energy management techniques may vary among vendor implementations.

Table 1: Lucent IEEE 802.11 WaveLAN PC Card Power Characteristics (Specification)

Doze Mode	9 mA
Receive Mode	280 mA
Transmit Mode	330 mA
Power Supply	5 V

This information can be used in combination with the IEEE 802.11 protocol definition to estimate the energy consumption associated with sending and receiving packets of various sizes. However, the specification does not show idle power consumption or fixed costs associated with operations such as carrier sense or changing state. It also excludes the effects of various energy management strategies.

5.2 Measurement Circuit

The measurement circuit was built using a Sycard PCCextend 140A CardBus Extender [5]. The extender is like a breakout box: it is inserted into the PC card slot on the host and the card to be tested is inserted into the card connector on the extender. The V_{cc} line can be isolated: a 1Ω resistor was inserted at this point. (The extender actually allows the entire interface to be examined using a scope or logic analyzer; it is usually used for testing and debugging PC cards.) See Figure 1. Voltage measurements were made using a 50MHz Fluke ScopeMeter 97 digital oscilloscope.

5.3 Network Configuration

The test host was an IBM ThinkPad 560, running on battery power. The software platform was FreeBSD and the freely available WaveLAN/IEEE driver written by Bill Paul (`wpaul@ctr.columbia.edu`). The test interface was a 2 Mbps Lucent WaveLAN

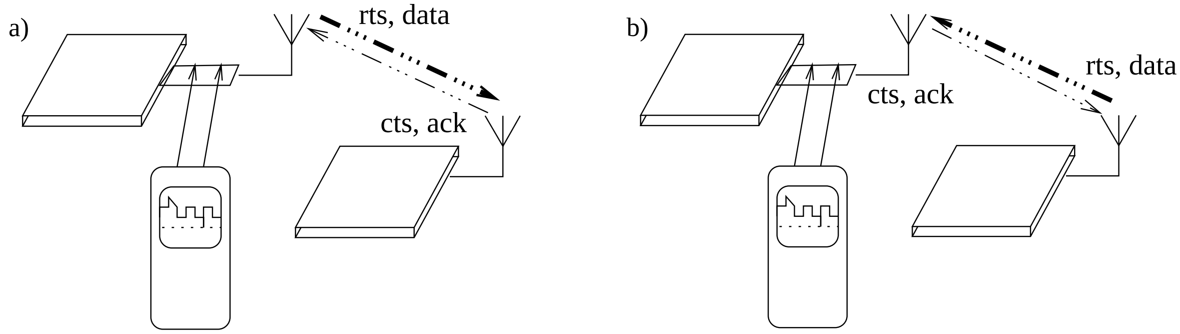

Figure 2: Measuring the energy consumption of (a) sending and (b) receiving traffic

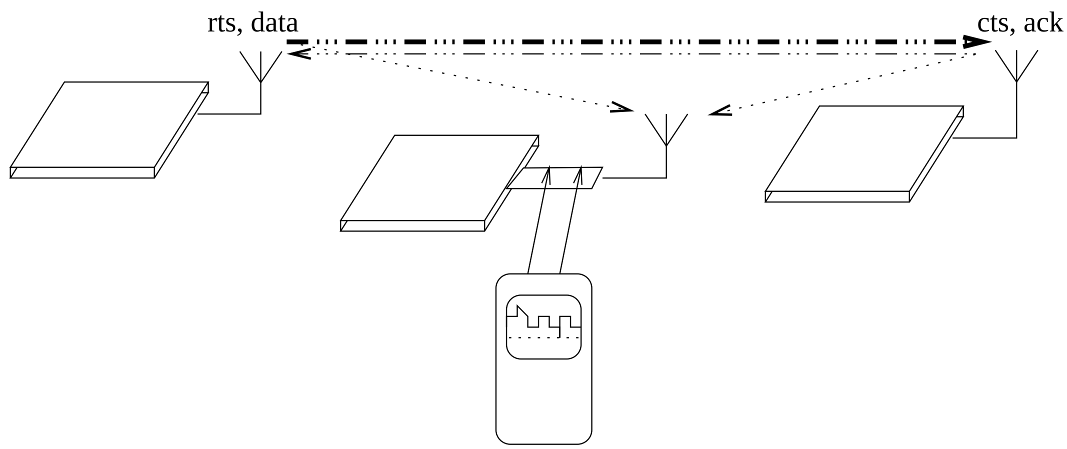

Figure 3: Measuring energy consumption of discarding traffic while in range of both sender and destination

IEEE 802.11 PC Card ("Bronze"). The same physical card was measured throughout the series of experiments. The rest of the experiment network consisted of a variety of IBM ThinkPad 560 and 570 laptops[1] and 2 Mbps Lucent WaveLAN IEEE 802.11 PC Cards (both "Bronze" and "White" models).

In order to measure the various scenarios required by the model, two different network configurations were used. For simple connectivity patterns, in which all hosts were in wireless range (Figures 2 and 3), the hosts were placed in close proximity, i.e. in same or neighboring offices.

Other connectivity patterns, (Figure 4) proved more difficult to reproduce completely consistently. In the SICS facility – which includes offices, conference rooms and a library area full of metal bookcases – fairly small distances were sufficient to disrupt network connectivity. Suitable locations were determined by walking around with

[1] The author would like to thank her colleagues for their support...

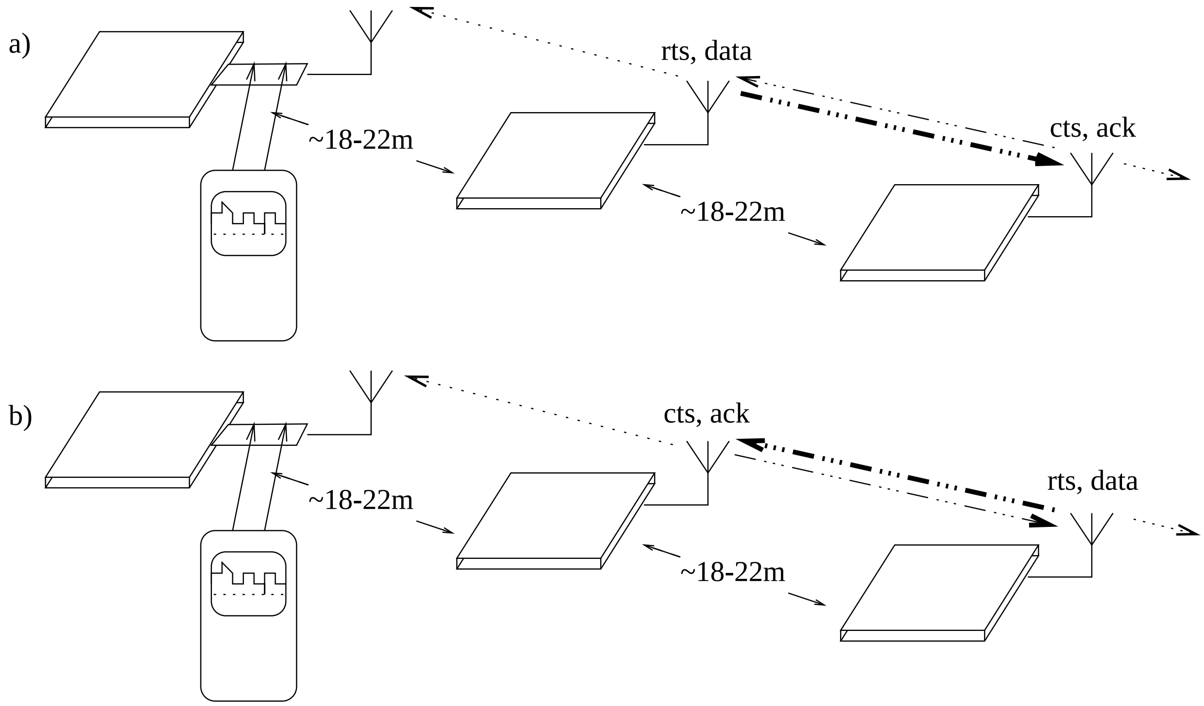

Figure 4: Measuring energy consumption of discarding traffic while (a) in range of the sender, but not the destination and (b) in range of the destination, but not the sender.

laptops running `'ping'` tests. Nodes intended to have connectivity were placed at physically convenient locations[2] several meters inside the range at which connectivity began to falter. Unidirectional connectivity was not considered.

5.4 Data Traffic

A simple program was used to generate UDP point-to-point and broadcast test traffic, sent at a rate of 20-30 packets per second. Total packet sizes ranged from 32 to 1024 bytes, including 8 + 20 bytes of UDP and IP header. The network MTU was set to 1500 bytes, so there was no fragmentation.

The Lucent WaveLAN IEEE 802.11 card supports a configurable RTS_`threshold`. For packets smaller than this threshold size, the data is sent in the "RTS" message. The destination responds with an ACK. This option was disabled for these experiments, ensuring that the full IEEE 802.11 protocol was used for all packets.

[2] The author would like to thank her colleagues for their support...

6 Visual Overview of Energy Consumption of the WaveLAN IEEE 802.11 Interface

This section provides a qualitative overview the energy consumption data. Some scope traces showing the current draw of the network interface during various operations are presented. Details of the IEEE 802.11 protocol described in Section 4 are clearly visible in scope traces and shown in the figures below. (Note that these plots are not actual scope traces. They were obtained by downloading waveform coordinates from the ScopeMeter via a serial cable interface and re-plotting them using 'gnuplot'.)

6.1 Point-to-point Traffic

For IEEE 802.11 point-to-point traffic (Figures 5, 6), the source listens briefly to the channel. If it is clear, the source sends an RTS (request-to-send) control message, identifying the destination. The destination responds with a CTS (clear-to-send) message. Upon receiving the CTS, the source sends the data and awaits an ACK from the destination.

The identification of the carrier sense just prior to sending the RTS is a little tentative, as the duration seems rather long and the data is rather noisy. Transmitting the 256 + 34 bytes (2320 bits) of data takes about 1.24 ms, slightly more than the anticipated 1.16 ms.

6.2 Broadcast Traffic

For IEEE 802.11 broadcast traffic (Figures 7, 8), the sender listens briefly to the channel. If it is clear, the message is sent. If not, the sender must back off and retry later. The IEEE 802.11 protocol does not define broadcast acknowledgement or retransmission.

Note that the power consumed while receiving data is not much greater than the idle power consumption. Especially because it is not bracketed by peaks associated with sending control messages, the trace of a host receiving broadcast traffic is somewhat more difficult to interpret.

6.3 Discard

To avoid collisions, the sender and receiver use the RTS/CTS control protocol is used reserve the channel for the duration of the data transmission. Hosts that overhear the control sequence must defer their transmissions until the channel is clear.

The trace shows that the WaveLAN interface enters a low-power mode during this interval in which it can neither send nor receive traffic. Because this requires less power than the idle mode – in which the interface is ready to receive traffic – the value of m_{disc}

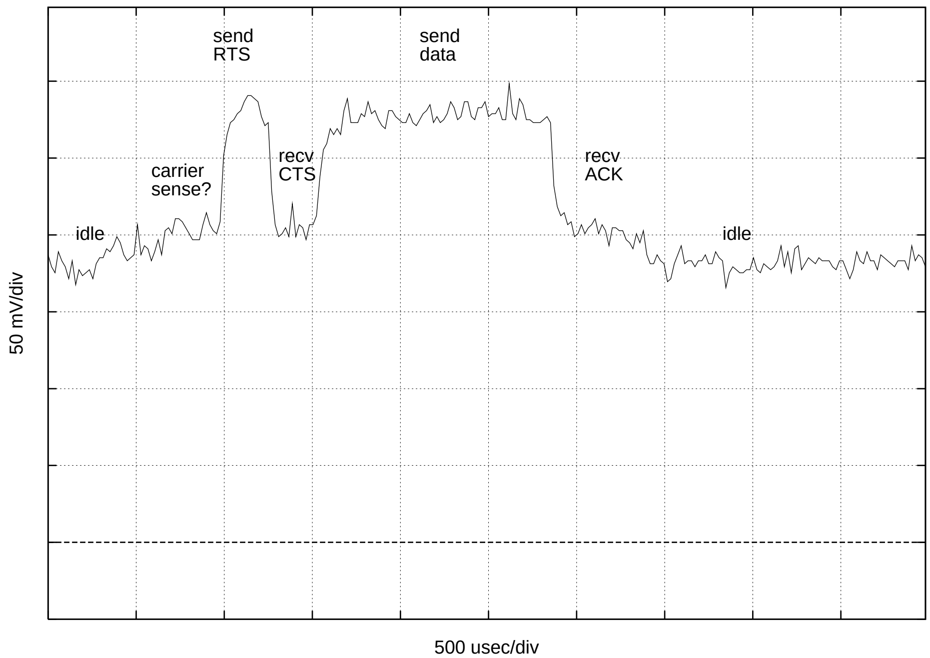

Figure 5: Sending point-to-point UDP/IP traffic (256 bytes)

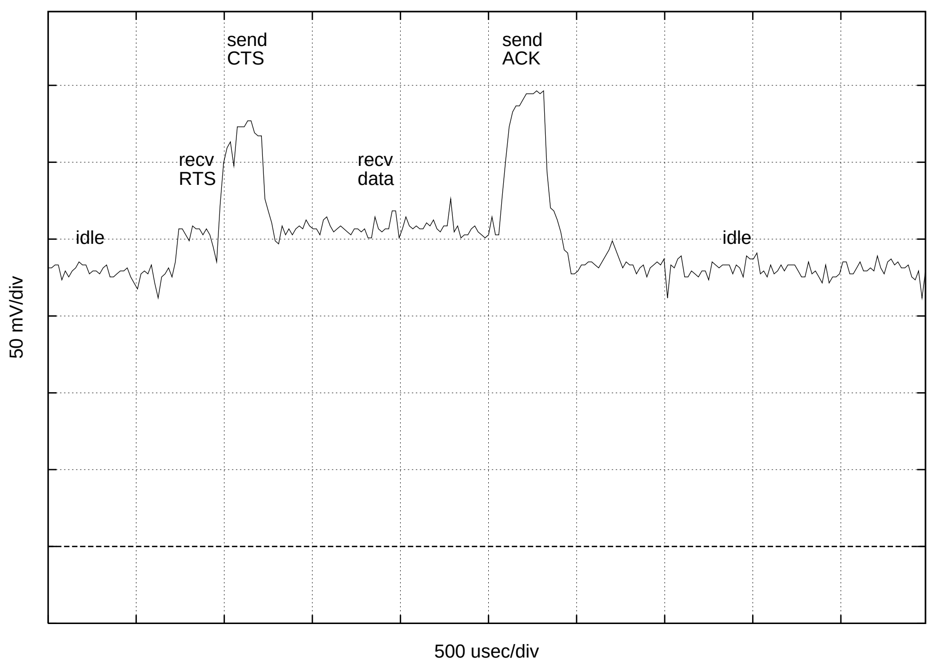

Figure 6: Receiving point-to-point UDP/IP traffic (256 bytes)

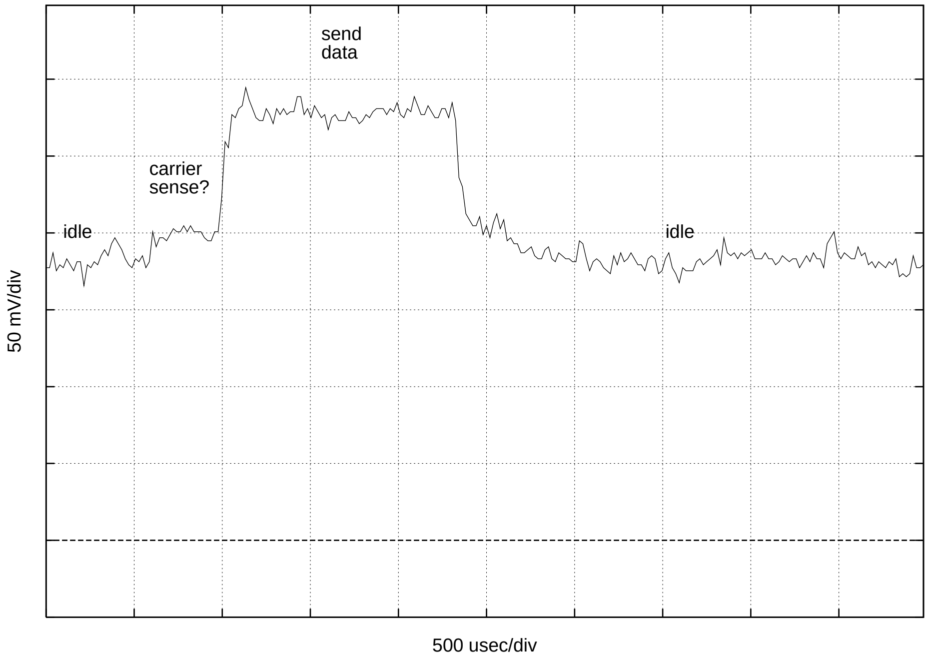

Figure 7: Sending broadcast UDP/IP traffic (256 bytes)

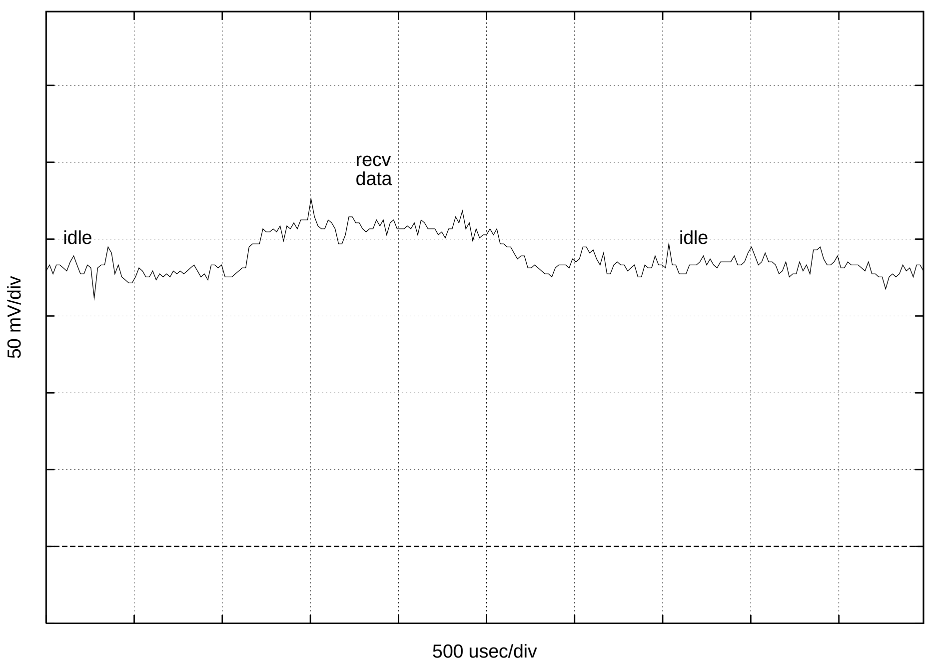

Figure 8: Receiving broadcast UDP/IP traffic (256 bytes)

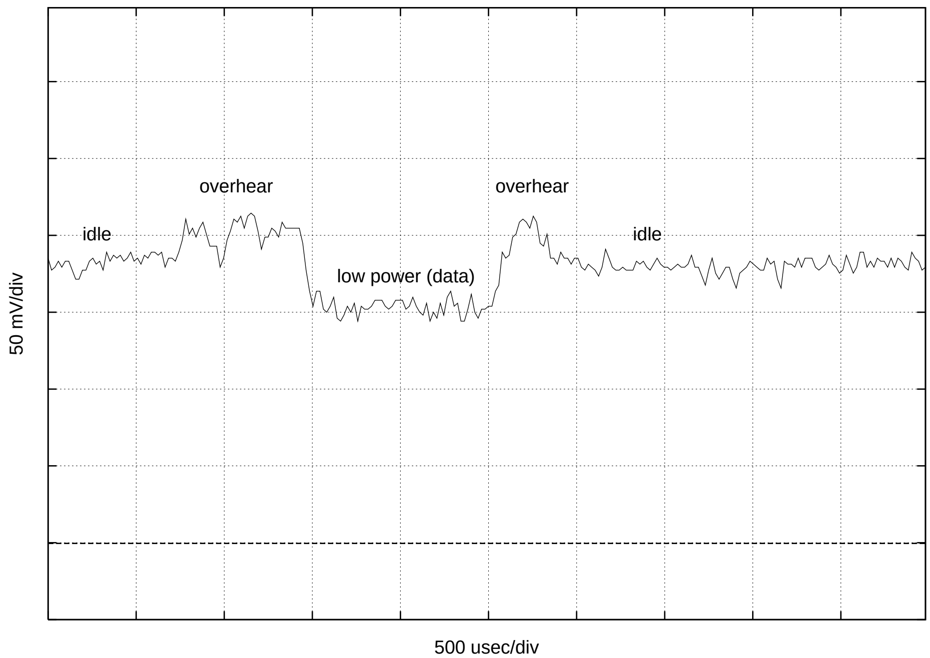

Figure 9: Non-destination host in range of both sender and receiver discarding point-to-point UDP/IP traffic (256 bytes)

is negative. This low-power mode has significantly higher power consumption than the documented “doze” mode (9mA), but is still noticeably less than the idle power consumption.

7 Determining Energy Consumption

The energy consumed by a host sending, receiving or discarding a packet is equal to the difference between the total energy consumed by the interface over the interval during which the packet was sent or received and the 'idle' energy consumption during the same interval.

The total energy consumption over an interval is integral of the instantaneous power consumption. This is the product of the (constant) input voltage and the integral of the current draw (= voltage across 1Ω resistor) over the interval. Figure 10 shows this being done using the ScopeMeter's built in integration function. limiting factor in these

The idle energy consumption over an interval is simply the product of the (constant) input voltage, the (constant) idle current and the length of the interval. One advantage of this differential approach is that it is not necessary to select the interval to correspond precisely with the packet event. As long as the “tails” on either side of the event are long

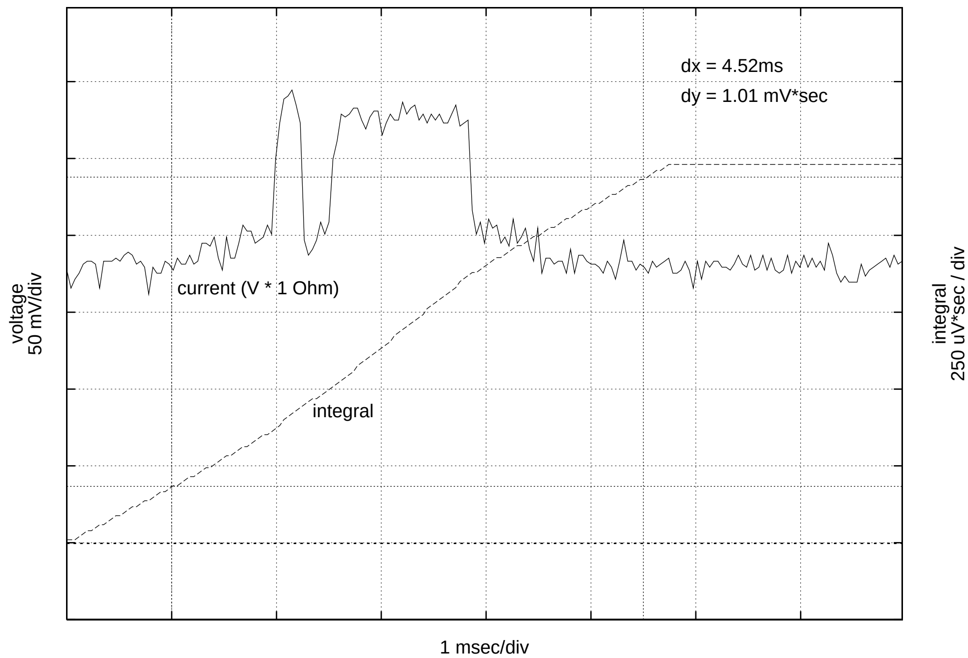

Figure 10: Computing the integral using the ScopeMeter (point-to-point send)

enough that any noise in the idle current is likely to be averaged out, their contribution to the total energy is subtracted out. However, the longer the tail, the smaller the contribution of network traffic to the total energy and the lower the resolution of the measurement.

Table 2: Lucent IEEE 802.11 WaveLAN PC Card Power Characteristics (Measured)

	exp't	max – min	nominal
Idle Mode	177 mA	174 – 182 mA	n/a
Receive Mode	204 mA	194 – 224 mA	280 mA
Transmit Mode	280 mA	272 – 288 mA	330 mA
Power Supply	4.61 V	4.58 – 4.62 V	5 V

Table 2 shows the values of the constants used in the energy consumption calculation. The input voltage at the interface was measured at 4.61V, with only slight variations. It was checked periodically to ensure that the that it had not dropped due to battery discharge.

The ScopeMeter's averaging function was used to determine that the average current draw while the interface was in idle mode was about 177mA. As is seen on the scope traces, there is considerable variation in the signal. However, the average current was fairly consistent over intervals as short as $500 - 1000\mu$sec.

Though not used in energy consumption calculations, values for the average current draw while receiving and transmitting data were determined in order to compare with the specification (Table 1). In general, the observed current draw during during data transmit and receive was lower than the nominal value. The reason for this discrepancy is not clear. The specification does not indicate what mode the card was in or other details about the measurement.

Finally, in order to separate per-packet energy consumption into fixed and incremental components, measurements were repeated for a variety of packet sizes. Linear regression was used to determine the slope and intercept. In general, the observed linear correlations were high, with absolute values over 0.97. Packets large enough to result in fragmentation were not considered.

8 Results and Discussion

Table 3 shows the complete energy consumption results, specifying linear coefficients for each relationship described in Section 4. The graphical representation in Figure 11 better shows the how the data reflects the behaviors that were expected based on the description of the IEEE 802.11 protocol.

1. Sending point-to-point (a) and broadcast (b) traffic have the same incremental cost, but point-to-point traffic has a higher fixed cost associated with the IEEE 802.11 control protocol. This is exactly as expected.

2. Receiving point-to-point (c) and broadcast (d) traffic show similar, rather than the expected identical incremental cost. As expected, the fixed costs differ significantly: Receiving point-to-point traffic has a very high fixed cost, due to the cost of sending the two control messages.

3. Receiving broadcast traffic (d) and receiving traffic in promiscuous mode while in wireless range of the sender (e, g) were expected to show the same incremental cost. They were also expected to have slightly different fixed costs, as the hosts overhear a different portion of the control sequence depending on whether they are in wireless range of the destination, while broadcast traffic has no control sequence. The data show that the three relations form a distinct cluster, with similar, though not identical slopes.

4. Non-destination hosts in range of the sender enter a reduced power consumption mode while data is being transmitted (f, h). Because this mode has lower power

[3]Excluding only MAC layer framing (34 bytes).

Table 3: Lucent IEEE 802.11 WaveLAN PC Card
2.4 GHz Direct Sequence Spread Spectrum
Linear Model Power Consumption Measurements

			$\mu W{\cdot}sec/byte^3$		$\mu W{\cdot}sec$
	sender $n = s$				
point-to-point send	Cost	=	1.9	$\times size$	+ 420
broadcast send	Cost	=	1.9	$\times size$	+ 250
	receiver $n = d$				
point-to-point recv	Cost	=	0.42	$\times size$	+ 330
broadcast recv	Cost	=	0.50	$\times size$	+ 56
	non-destination $n \in \mathcal{S}, \mathcal{D}$				
promiscuous recv	Cost	=	0.39	$\times size$	+ 140
discard	Cost	=	-0.49	$\times size$	+ 97
	non-destination $n \in \mathcal{S}, n \notin \mathcal{D}$				
promiscuous recv	Cost	=	0.54	$\times size$	+ 66
discard	Cost	=	-0.58	$\times size$	+ 24
	non-destination $n \notin \mathcal{S}, n \in \mathcal{D}$				
promiscuous "recv"	Cost	=	0.0029	$\times size$	+ 63
discard	Cost	=	-0.0058	$\times size$	+ 56
idle	Cost	=	808 mW		

consumption than the idle mode, the incremental cost of ignoring data is negative. The incremental cost was expected to be the same regardless of whether the host was also in wireless range of the destination. The fixed costs were expected to differ slightly due to the hosts overhearing different parts of the control sequence. The data show that the relations have similar, though not identical, slopes.

5. For a non-destination host in range of the destination, but not the sender (i), there is no corresponding energy conserving strategy. Neither this host nor a similarly located host operating its network interface in promiscuous mode (j) overhear data because they are not in range of the sender. The observed incremental cost is very close to the expected value zero.

6. A non-destination host must process and ignore control traffic, regardless of whether it goes on to discard or eavesdrop on the data traffic. It was therefore expected that the fixed cost would depend only on what portion of the control protocol the host overheard. Non-destination hosts in range of both sender and destination (e, f), in range of the sender only (g, h) and in range of the destination only (i, j) were expected to have the same fixed costs. The data show that the fixed cost

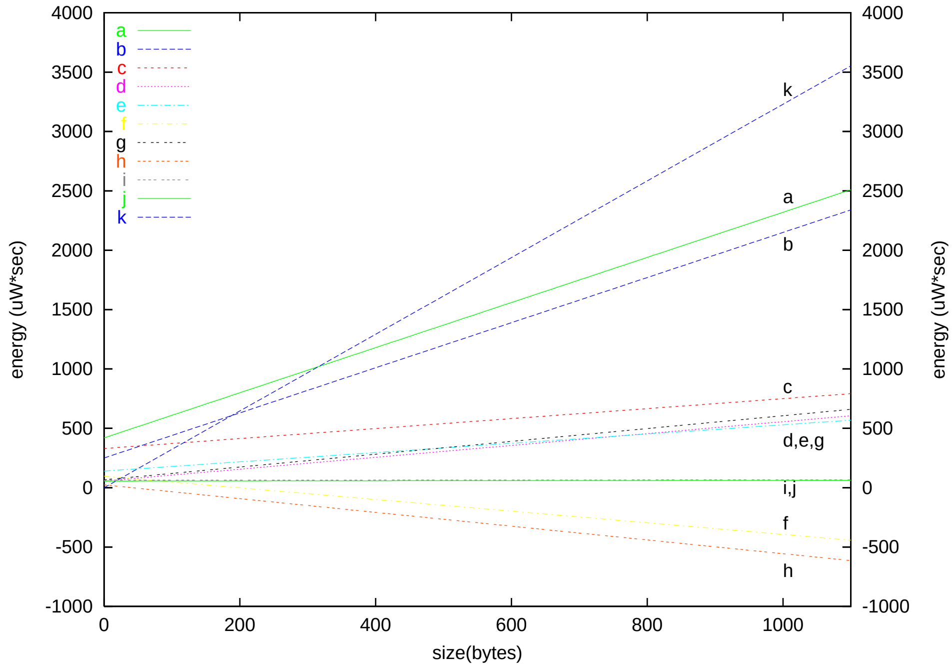

Figure 11: Experimental results

was noticeably higher for a host operating in promiscuous mode, particularly in the case of a host in range of the sender.

The cause of this discrepancy is not clear. It is possible that the expectation was not correct: The energy management strategy used by non-destination hosts may also reduce fixed costs in some way that is not clear from the scope trace. It is also possible that operating the network interface in promiscuous mode makes other operations more expensive: however, it is known *not* to increase the idle mode power consumption.

7. The relative magnitude of the idle energy consumption is indicated by (k), which shows the energy consumed by an idle interface in an interval equivalent to the time it take to transmit *size* bytes at 2 Mbps. The interface has very large idle energy consumption when it operates in ad hoc mode: addressing this problem will be very important in the development of mobile ad hoc networks.

The experimentally determined relationships show fairly good agreement with expectations based on the definition of the IEEE protocol.

There are a number of potential sources of experimental error. One interesting possibility is that the amount of processing (energy) required to receive a packet depends significantly on received signal strength and/or ambient interference. The relatively high incremental cost of receiving data is partly due to extensive signal processing performed at the receiver. If this processing requires significant computation, it may also require more energy. This effect may be difficult to quantify without much more specialized equipment and a more controlled wireless environment.

9 Further Investigation

Investigation into both the energy consumption behaviors of the WaveLAN IEEE 802.11 interface and techniques for measuring the energy consumption of networked mobile devices is continuing.

The WaveLAN card supports a number of options, including the RTS optimization described earlier and reduced transmit rates (which have greater range). Their effect on energy consumption has not been documented.

The data is not currently precise enough to determine the cost of individual low level operations, such as the sending and receiving of control messages. An improved experimental circuit may address this. It may also be possible to make measurements that are precise enough to quantify the effect of signal strength on energy consumption.

The effects of retransmissions and other errors have not yet been investigated. It is unlikely that these events will occur with sufficient frequency to significantly effect long term energy efficiency at an interface. Nevertheless, this behavior should be considered, at least qualitatively.

These experiments measured the behavior of the network interface operating in ad hoc mode. When operating in cooperation with a base station, the system constraints change dramatically. The network interface optimizes for spending as much time as possible in a very low power 'doze' mode, relying on the base station to schedule communication and buffer traffic. This also reduces the need for the collision avoidance protocols used in ad hoc mode, but it also leads to a much more complex base station - mobile host protocol. This may may also make it more difficult to measure the energy consumption of an interface operating in base-station mode using experiments such as those described above.

More important than additional measurements, the results also suggest interesting areas for protocol development. At the MAC layer, the extremely high idle mode energy consumption is clearly an important issue. At the network layer, protocols that adapt to local node density can, to some extent, control the amount of energy consumed in receiving or discarding traffic. The relatively low incremental cost of sending data suggests that aggregation schemes may have some value.

10 Conclusions

The results of this very simple series of experiments show that the energy consumption of an IEEE 802.11 wireless interface has a complex range of behaviors. While the specific results have only a small practical value, the absolutely essential overall lesson is that energy consumption must be treated as a network layer issue, as well as a MAC layer one. Protocol design and evaluation should include factors such as the relative proportions of broadcast and point-to-point traffic, packet size and reliance on promiscuous mode operation.

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I would particularly like to thank Martin Nilsson (SICS) for his expert advice on practical issues in circuit design. I would also like to thank my colleagues in the Computer and Network Architecture Laboratory at SICS for their support.

In addition to basing my experimental setup on that described in [2], I was also inspired by the directness and novelty of these experiments.

Thanks also to Mike Mori of Sycard Technology for permission to reproduce Sycard circuit diagrams.

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